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Using fire dynamic simulation (FDS) to reconstruct an arson fire scene

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Abstract

Fire scene reconstruction helps investigators identify the fire behavior in a specific space. Fire scene simulation by using computation fluid dynamic (CFD) software may provide evidences for fire investigation. Such simulation method may reproduce the fire scene, reconstruct fire processes, explain fire development and demonstrate smoke movement through describing the configuration of fuel, effects of ventilation, design of the building, the impact of manual or automatic systems and fire source. Comparing simulation results with investigation collections, we can get more evidences toward the fire and smoke development. This paper used FDS (Version 4.0.5), especially using parallel processing [McGrattan and Forney. Fire dynamics simulator (version 4.05)—user's guide. National Institute of Standards and Technology, Maryland, 2005. p. 7.] approach, to simulate a hotel arson fire in Taiwan. Its results demonstrated good prediction of fire development and smoke movement by comparing the combustion evidence of the scene and evacuees' description. This article also provides application of fire simulation into actual fire scene investigation.
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Keywords: Parallel processing; Fire scene reconstruction; FDS; Fire simulation; Fire investigation

1. Introduction

The investigation result of the fire not only offers the references to make and adjust the fire safety policies, but also gives the important professional opinions to the judicial authorities to use to identify the civil and criminal responsibility. With the development of fire science, courts are now inclined to use scientific methods in demonstrating the evidence of the fire scene. Therefore, fire simulation becomes an important tool in fire investigation [1].

NFPA 921 [2] defines fire scene reconstruction as:

Fire scene reconstruction is from one of the fire it ignites to go out in the fire scene, can explain the dispositions of fire and smoke development, the situation of flammable thing distribution, ventilation effects, and the effects of manual or automatic suppress equipments, the design-ing of building itself, characteristic and casualties of the human life safety devices, etc.

These include the projections of fire damage, fire science and engineering, human behavior factors, material evidence and adopted suitable scientific methods, etc. The result of these calculations (for instance, burning time, temperature, height of flame and smoke layer and spreading, etc.) compared with the real situation in the fire scene can guide the investigation direction. It is useful in judging the burning sequence of flammable materials, contributes to tracing the burning direction to narrow the area of the origin of a fire, and then seeks the rational, accurate cause of fire [3].

2. A hotel arson fire in Taiwan

The hotel fire happened in Taoyuan city, Taiwan at 08:25 AM in November 2003. The building had 10 floors and of multi-occupancy, including pubs, wine shops, disco clubs, residences, a disabled persons association, and the hotel. The 6th and the 7th floors incorporate the hotel and

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Nomenclature

A	area (m^2)
k	thermal conductivity; suppression decay factor (W/m/K)
ρ	density (kg/m^3)
Cp	constant pressure specific heat (kJ/kg/K)
D	diameter of the fuel bed (m)
L_f	the flame height above the fuel surface (m)
L	liter (L)
D^*	characteristic fire diameter
Q^*	total heat release rate (kw/m^2)
T	temperature (k)
t	time (s)
ΔHc	heat of combustion (MJ/kg)

have the same floor configuration. The initial fire was at a service counter on the 7th floor, where the main damage was also located. The fire was arson, caused by gasoline poured on the hallway carpet. The fire started quickly and the smoke spread too fast for the occupants to escape, causing 5 fatalities on the floor of the fire origin and 10 injuries on other floors.

2.1. Information from the floor of the fire origin [4]

The fire began on the 7th floor of the hotel. The layout of this floor is described in Fig. 1. The background details of the floor can be seen in Table 1. The burned materials are included in Table 2 and Figs. 2–4.

Table 1
Background details for the 7th floor

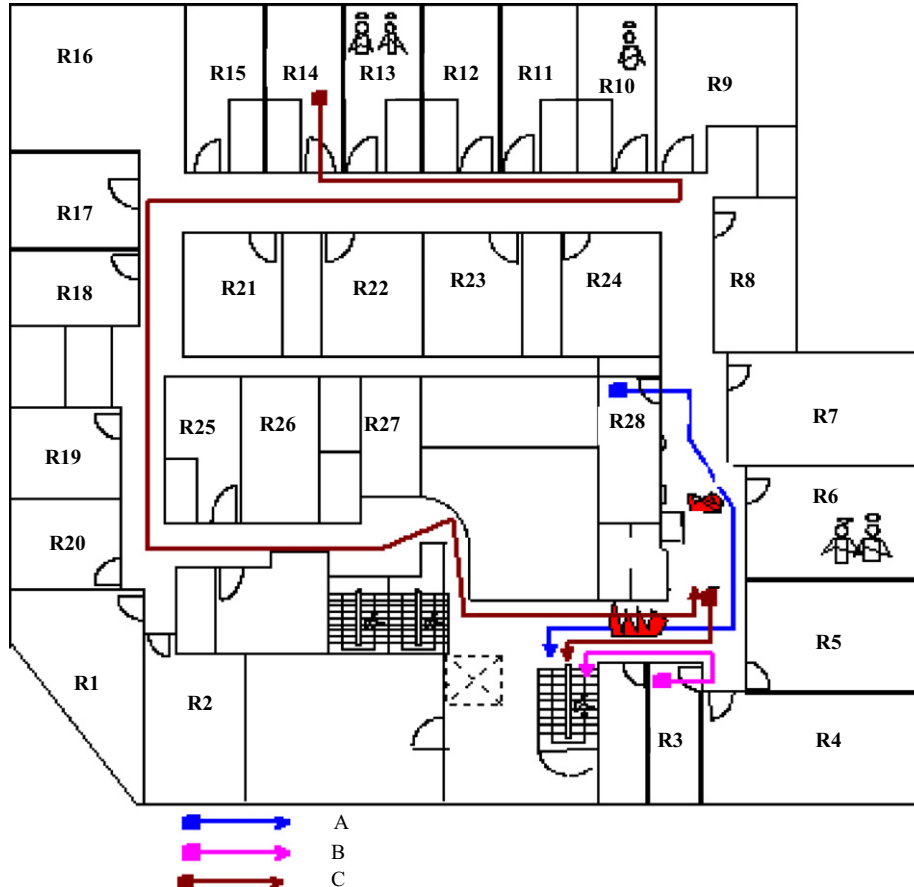|	
Space dimension	46 m × 31 m × 3 m
Floor height	2.8 m
Area	45 m × 30 m = 1350 m^2
Ceiling height	2.2 m
Initial temp	20 °C
Rooms in floor	(Service counter, storage room, stockroom, office, public toilet) × 1, 28 rooms (described in Fig. 1)
Wall material	Exterior wall: concrete
	Interior wall: gypsum board (0.15 m thickness)
Ventilation	Atrium 6 m × 6 m = 36 m^2, lobby height 5.8 m, window closed

Fig. 1. Layout and escape routes in the 7th floor.

Table 2
List of burned materials

Item	Combustible material	Size/number
2 Room service trolleys	Towel, bed sheet, trash bag	Towel, bed sheet: (0.7 m × 1.0 m × 0.25 m) × 4 Plastics pad: (0.7 m × 1.0 m × 0.04 m) × 4 Trash bag: (0.7 m × 0.7 m × 0.15 m) × 1
Service counter	Towel, bed sheet, cloth, pillowcase, bed quilt, office chair	Towel, bed sheet, cloth: (2.0 m × 0.25 m × 0.2 m) × 6 Pillowcase, bed quilt: (2.0 m × 0.25 m × 0.2 m) × 2 Office chair: (0.5 m × 0.5 m × 0.15 m) × 2
Storage room	Backup things like paper cup, clothes, paper box	Towel, bed sheet, cloth: (2.0 m × 1.0 m × 0.2 m) × 6 PUF: (2.0 m × 1.0 m × 0.2 m) × 2
Carpet	Thickness 10 mm	At the base of floor without extensible burning
Wood sheet	Service counter, storage room, stockroom, all applied wood sheet	Cabinet: (1.0 m × 1.0 m × 2.2 m) × 1 (thickness 0.02 m) Service counter, storage room, stockroom: (1–2 m × 1–2 m × 1–2.2 m) × 10 (thickness 0.02 m)
Lobby	Decorated with wood sheet	(1–2 m × 1–2 m × 1–2.2 m) × 4 (thickness 0.02 m)
Accelerant	Gasoline	(0.8 × 0.8) m² location 1 (0.6 × 1.0) m² location 2

Humidity: normal 60–70%

2.2. Occupant behavior in the floor of fire origin

Table 3 and Fig. 5 are produced based on the interviews with some successful evacuees. The information can be used to depict the fire development.

3. Fire simulation using FDS

3.1. FDS model description

Fire dynamics simulator (FDS) is a computational fluid dynamics (CFD) model that describes the flow of smoke and hot gases from a fire. It solves numerically the Navier–Stokes equations appropriate for low-speed, thermally driven flow on smoke and heat transport from fires. FDS has been aimed at solving practical fire problems in fire protection engineer, while at the same time providing a tool to study fundamental fire dynamics and combustion. There is a distinguishing feature, the k–ε turbulence modeling, applied in FDS. It can describe fires in complex geometries, and the incorporation of a wide variety of physical phenomena. It also can be used for introducing large eddy transport coefficients to describe the unresolved fluxes of mass, momentum and energy. Now, the model has been applied for performance-based fire safety designs, designs of smoke control systems, sprinkler/detector activation studies, and residential/industrial reconstructions described in Table 4. It will also become a useful tool in fire investigation and fire scene reconstruction.

3.2. Design fire

The hotel fire is an incendiary event caused by the spilling and ignition of gasoline on the carpet. After a detailed fire
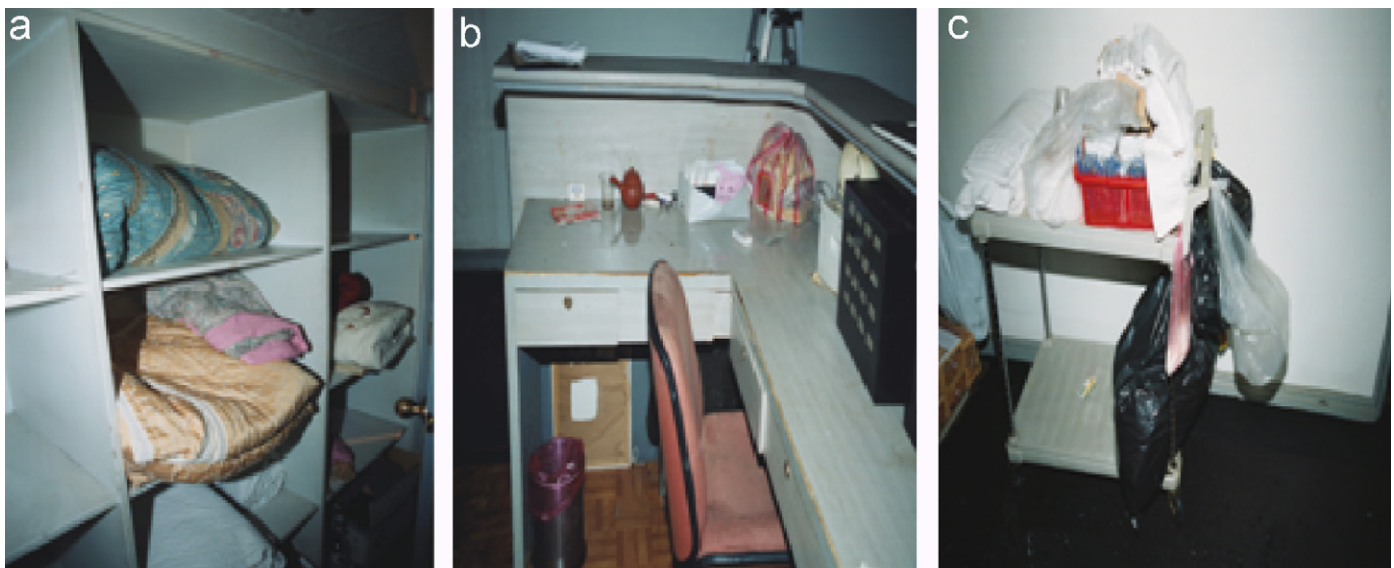

Fig. 2. (a) Storage room, (b) service counter, and (c) room service trolley.

Fig. 3. (a) 6F service counter and (b) 7F service counter.

Fig. 4. (a) 6F storage room and stockroom and (b) 7F storage room and stockroom.

scene investigation on the burned area, and thickness (10 mm) of the carpet, the quantity of the flammable liquid at the scene could be reasonably predicted.

a. The first burned area contained gasoline $0.8 \, \text{m} \times 0.8 \, \text{m} = 0.64 \, \text{m}^2$, almost 6–7 L; gasoline density is $0.74 \, \text{kg/L}$, almost 4.8 kg.
b. The second burned area contained gasoline $1.5 \, \text{m} \times 0.6 \, \text{m} = 0.9 \, \text{m}^2$, almost 9 L; gasoline density is $0.74 \, \text{kg/L}$, almost 6.66 kg.
c. Calculation of the heat release rate (HRR) of gasoline $Q = 0.036 \, \text{kg/m}^2 \times 43.7 \, \text{MJ/kg} = 1573 \, \text{kw/m}^2$.
   The total amount of gasoline was almost 15 L, which is a reasonable value in the consideration of inconvenience to carry gasoline to the fire scene.
d. Burning time:

$$T = \text{gasoline weight/burning rate (m/s)}$$
$$= \text{Area } (A) \times \text{Thickness} \times \text{Density/burning rate (m/s)}$$
$$= 0.8 \, \text{m} \times 0.8 \, \text{m} \times 0.01 \, \text{m} \times 0.74(\text{kg/L})/0.8 \, \text{m} \times 0.8 \, \text{m}$$
$$\times 0.036(\text{kg/m}^2 \, \text{s}) = 205 \, \text{s}.$$

Taking 210 s, if we assume a burning efficiency of 0.8, the total burning time is about 260 s.
e. The height of the flame

$$\text{HRR} : Q = 0.036 \, \text{kg/m}^2 \times 43.7 \, \text{MJ/kg} \times (0.8 \, \text{m} \times 0.8 \, \text{m})$$
$$= 1006 \, \text{kw}.$$

HRR corresponds to the limitation of Heskestad's correlation: $0.12 < Q < 1.2 \times 10^{10}$ (kw) [5]

$$\text{Flame height} : L_f = 0.23Q^{2/5} - 1.02D$$
$$= 0.23(1006 \, \text{kw})^{2/5} - 1.02(0.8 \, \text{m})$$
$$= 2.83 \, \text{m}.$$

The value of $(Q^{2/5}/D)$ fits the range of limitation: $7 < Q^{2/5}/D = 19.81 < 700$ (kw$^{2/5}$/m).

The value is sufficient to reach the ceiling height of 2.2 m and agrees with witness statements [6].

3.3. Simulation

All meshes are cut to 10 cm × 10 cm × 10 cm grids. Based on the D^* evaluated method of accuracy, the dimension of

Table 3
Actions of successful evacuees in fire

| Occupant	Position	Time analysis
A	Tenant in Room 28, the first one to discover the fire	Smelled the smoke odor from hallway, called service counter E and then found that the fire reached ceiling at the room service trolley, escaped to the 6th floor (about 20 s passed), took elevator to the 1st floor (about 100 s passed).
B	Tenant in Room 3, the first client received fire alarm from service counter	Immediately escaped from the room without closing the door. When she passed by the storage room, there is no fire over there (about 25 s passed).
C	The manager of the hotel, the first person received fire alarm from service counter	Went from Room 14 to Room 9 corner and found the smoke increased fast (about 30 s passed), ran in the opposite direction through lobby to R6, R28, R7 hallway and extinguished the fire in front of the service counter. There is no fire in storage room at that time (about 60 s passed).
D	Service clerk in the 7th floor	Ate in the 6th floor, received the fire message from clerk E and went to the 7th floor found that the hallway to service counter full of smoke (about 30 s passed).
E	Service counter clerk in the 6th floor	Received message from tenant A, immediately notified clerk C, D, and tenant B to escape, then called Room 6 but nobody answered the phone and soon the phone line broke (about 60 s passed), alarm actuated (about 90 s passed), power failure (about 100 s passed).
F 3 Occupants	Tenants in Room 26	Smelled the odor of smoke and asked the service counter about the situation (about 30 s passed), then opened the room door and found the hallway full of smoke (about 80 s passed), asked service counter clerk to actuate the alarm, and it worked (about 90 s passed). At that time, fire grew up greatly. The total period was less than 3 min.
G	Tenant in Room 4	Finished eating in the 6th floor and walked to the 7th floor, found the 7th floor hallway full of smoke without light. At that time the clerk was notifying other tenants (about 15 s passed). Another one called ambulance (Tel: 911) and then tenant A ran down the stair (about 20 s passed).
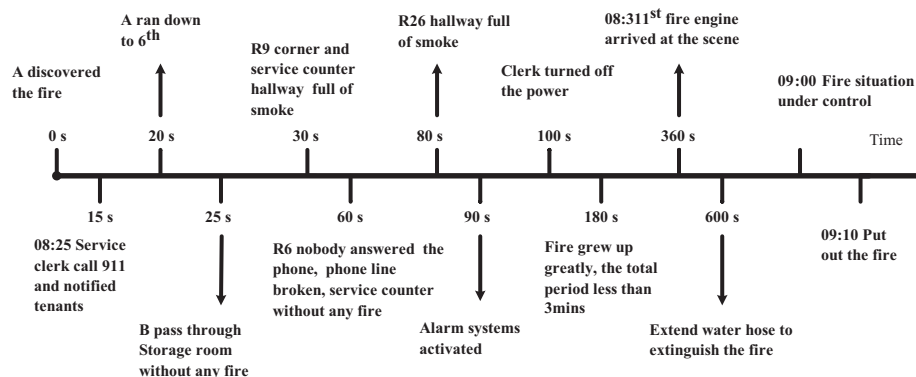
Fig. 5. Timeline [2] based on evacuee's descriptions.

the grid is suitable for the case. There are a total of 4.4 million grids in the calculated area. Total grids are distributed into 18 computers to execute parallel processing and use one server CPU to collect the data from each computer. The CPU of each computer is 2.8 GHz and the memory is 768 MB. The division of the calculated area is described in Fig. 6. It takes 90 h to complete a simulation, and the final HRR is as Fig. 7.

3.4. Temperatures of simulations

The burning temperature of gasoline is 1026 °C, similar to the temperature in the simulation (1020 °C). The stripes on the right side of the figure represent a summary of the visual observations, with the black stripes representing

ignited temperature 260 °C of wood, the orange ones external flaming, and the yellow portions fires that were seen inside the building. The red areas represent numerical prediction of temperature near the service counter of 1020 °C, a typical fully involved fire. The temperature profiles of the fire scene are calculated and described in Table 5 and Figs. 8–11, based on the escape time of the evacuees.

3.5. Smoke propagation in simulations

The smoke propagation profiles of the fire scene are also assessed in accordance with the escape times (20, 100, 300, 600 and 870 s) of relevant personnel at the scene. They are demonstrated in Table 6 and Figs. 12–18.

Table 4
Cases of FDS applications

| Area of application	Cases	Contents
Performance-based fire safety design	Taipei Arena, 2000	Time of smoke layer descending
		Temperature
	Taiwan High speed rail station, 2003	Time of smoke layer descending
		Visibility
		Temperature
		Concentration of CO and CO_2
	Taipei financial center (Taipei 101), 2003	Same as above
	Miramar Entertainment Park, 2004	Same as above
Fire scene investigation and reconstruction	Simulation of the dynamics of the fire at 3146 Cherry Road N.E., Washington, DC, May 30, 1999.	Temperature
		Concentration of CO and CO_2
	Computer simulation of the fires in the World Trade Center Towers 2005.	Smoke propagation
		Visibility
		Temperature
		Layout of fuel and structure
		Interviews with successful evacuees and witnesses
	Using fire dynamic simulation (FDS) to reconstruct an arson fire scene 2006	Smoke propagation
		Visibility
		Temperature
		Layout of fuel and structure
		Interviews with successful evacuees and witnesses
		Timeline
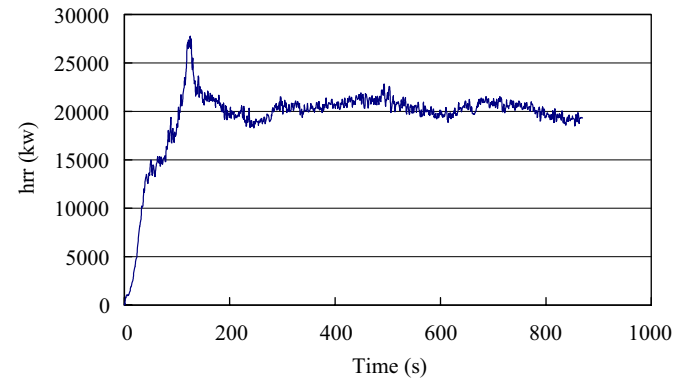
Fig. 7. HRR curve.

Table 5
Temperature profiles

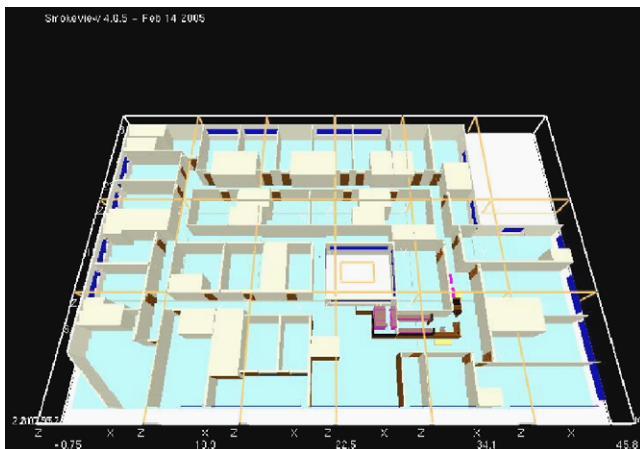| Location	Time (s)	Ceiling temperature (°C)
Fire origin	20	500–700
	100	900–1020
	300	900–1020
	600	800–900
	870	800–900
Service counter	20	50–100
	100	400–500
	300	700–800
	600	800–1000
	870	700–800
Storage room	20	50–100
	100	200–300
	300	400–600
	600	700–800
	870	500–600
Lobby	20	30–50
	100	100–200
	300	400–600
	600	700–800
	870	700–800
R10 hallway	20	30–50
	100	200–300
	300	300–400
	600	300–400
	870	200–300
R18 hallway	20	30
	100	30–50
	300	50–100
	600	50–100
	870	50–100

4. Result discussions

4.1. Influence of grid sizes [7]

In executing parallel processing, it is important to consider the problem of data exchange at the mesh interfaces. Different sizes of grids also produce unstable

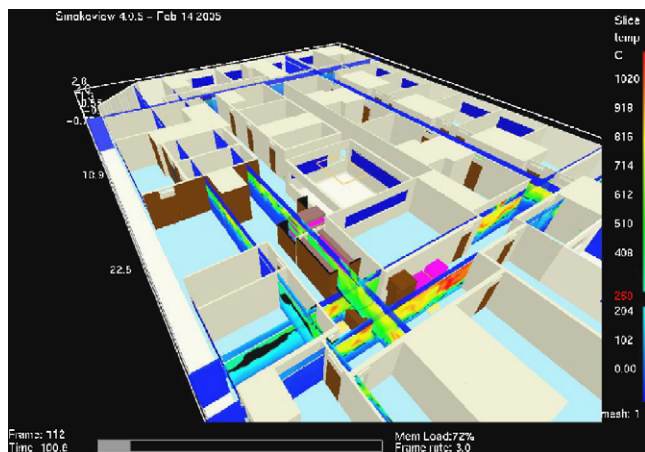Fig. 6. FDS 10 cm grids designed figure.

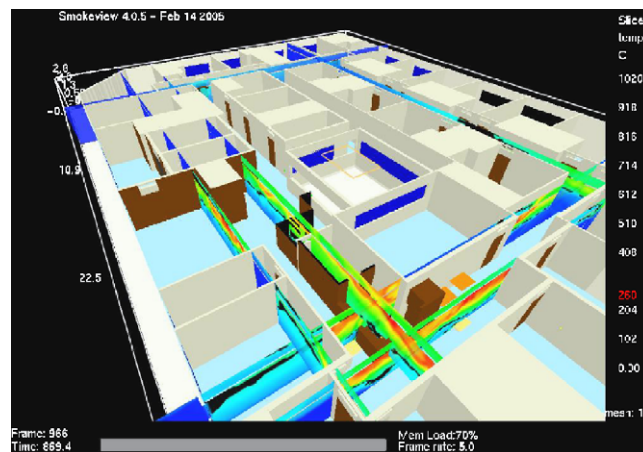Fig. 8. Temperature profile (100 s).
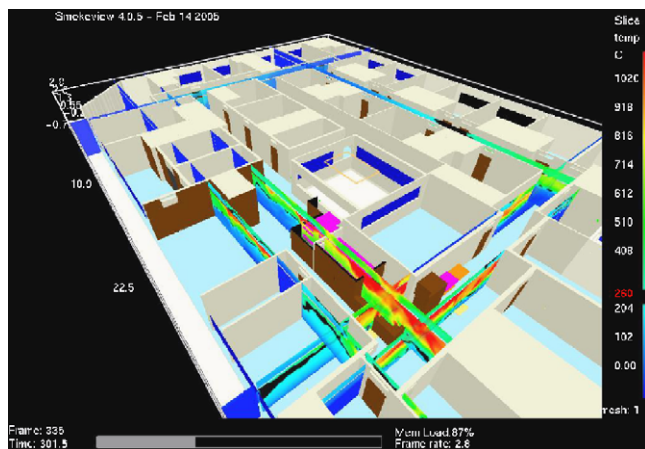

Fig. 11. Temperature profile (870 s).

Fig. 9. Temperature profile (300 s).
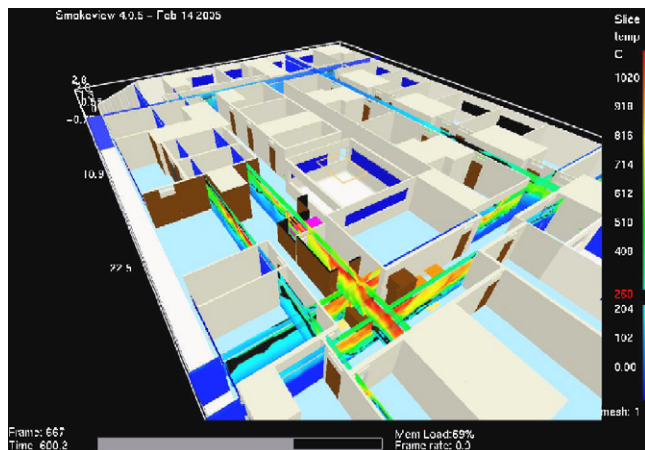

Fig. 10. Temperature profile (600 s).

Table 6
Smoke propagation profiles

Location	Time (s)	Height of smoke layer (m)
Fire origin	20	Less 1.5
	100	−0.3
	300	0 (smoke layer down to the floor)
	600	0
	870	0
Service counter	20	2
	100	0.5
	300	Less 0.3
	600	Less 0.3
	870	Less 0.3
Storage room	20	2
	100	0.5
	300	−0.3
	600	−0.3
	870	−0.3
Lobby	20	2
	100	0.5
	300	−0.3
	600	−0.3
	870	−0.3
R10 hallway	20	1.5
	100	0
	300	0
	600	0
	870	0
R18 hallway	20	2.2
	100	0
	300	0
	600	0
	870	0

situations, which sometimes have no explanation. To try to achieve stability in the calculation, this paper adopted grids of the same size to simulate the fire development.

The grid size will influence the result of the simulation. The maximum temperature of simulation with a grid size of 15 cm is 670 °C. However, the maximum temperature of a simulation with 10 cm grid sizes is 1020 °C. The latter's (10 cm of grid size) prediction is more reasonable and the burning temperature of the fire source corresponds to the design fire.
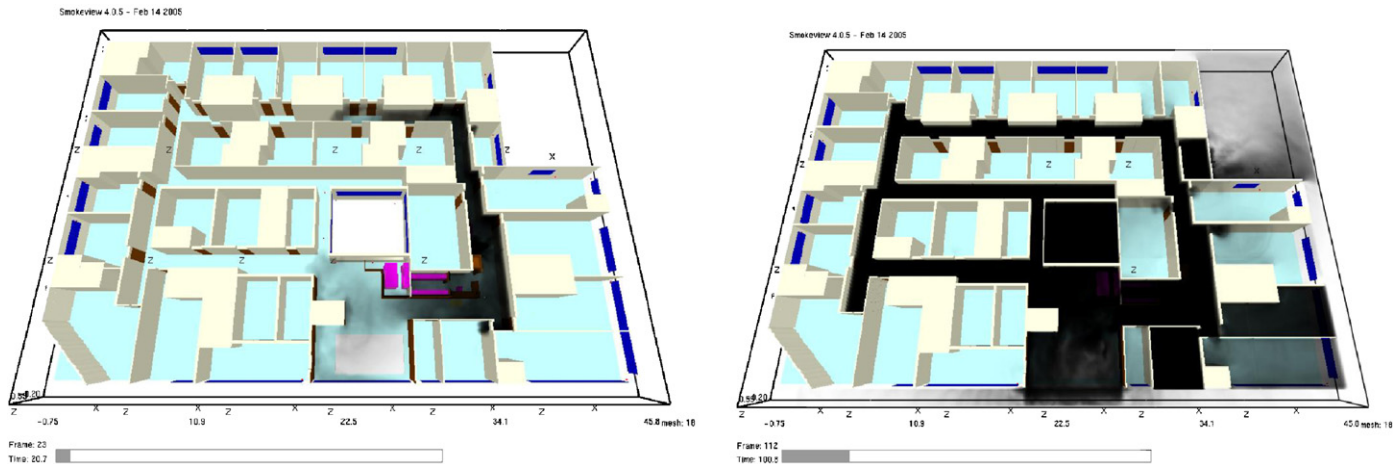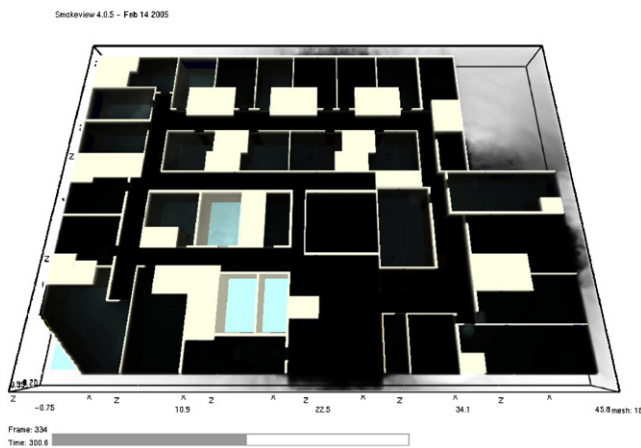
Fig. 12. Smoke propagation profiles (20 s, 100 s).

Fig. 13. Smoke propagation profile (300 s).

4.2. Temperature of the simulations

It was the gasoline that ignited the fire. The temperature of burning gasoline is 1026 °C, which is a negligible difference with the simulation temperature of 1020 °C. And the temperature profile of the calculation agrees closely with the description of evacuees, based on the comparison at different escape times. The HRR curve is stable and conforms to the time line of fire scene investigation of the evacuees. This is the qualitative assessment.

4.3. Smoke propagation analysis

The smoke movement simulation shows that if the narrow hallway of the hotel were ignited with the accelerating agent, heavy smoke would spread along the hallway rapidly and obstruct the escape paths. The smoke layer would also become lower to the floor level within 100 s. All rooms would be filled with thick smoke in

300 s. This scenario complies with the investigation into the escape of occupants.

4.4. Smoke movement to life safety

The results of the simulation indicate that the temperature around the hallway at the fire source reached 500 °C at 20 s from the initial period. In that situation, everyone would be trapped in the room unless they discovered the fire at its early stage and escaped immediately. The narrow, long hallway, 2.2 m wide and 1.8 m high was shrouded in heavy smoke immediately in the initial stages of the fire. It was impossible to move along the hallway at 100 s. Smoke then continued to invade rooms adjacent to the hallway through ventilation shafts. Smoke poured into Room 6 due to its very close proximity to the fire location. Rooms 10 and 15, although far from the fire's origin, also had heavy smoke invasion and had two victims. At 300 s, the environment of the two rooms had become too dangerous for occupants.

5. Concluding remarks

This research hopes to predict the development of heat, smoke and toxic gases at the fire scene using simulation software, thereby supporting the work of fire scene investigation. The main conclusions are:

(1) It is very clear that the cause of this hotel fire was the ignition of the accelerating agent. This discovery may be enough for today's fire investigation in Taiwan. However, more important is identifying how the fire spread and how deaths and injuries occurred. The simulation results indicate that the cause of the fire spreading to the service counter or other spaces is due to the sufficient heat release rate of the fire source in igniting the trolley, cloth and disposal bag in the hallway. If the rate of the fire spreading had not been as
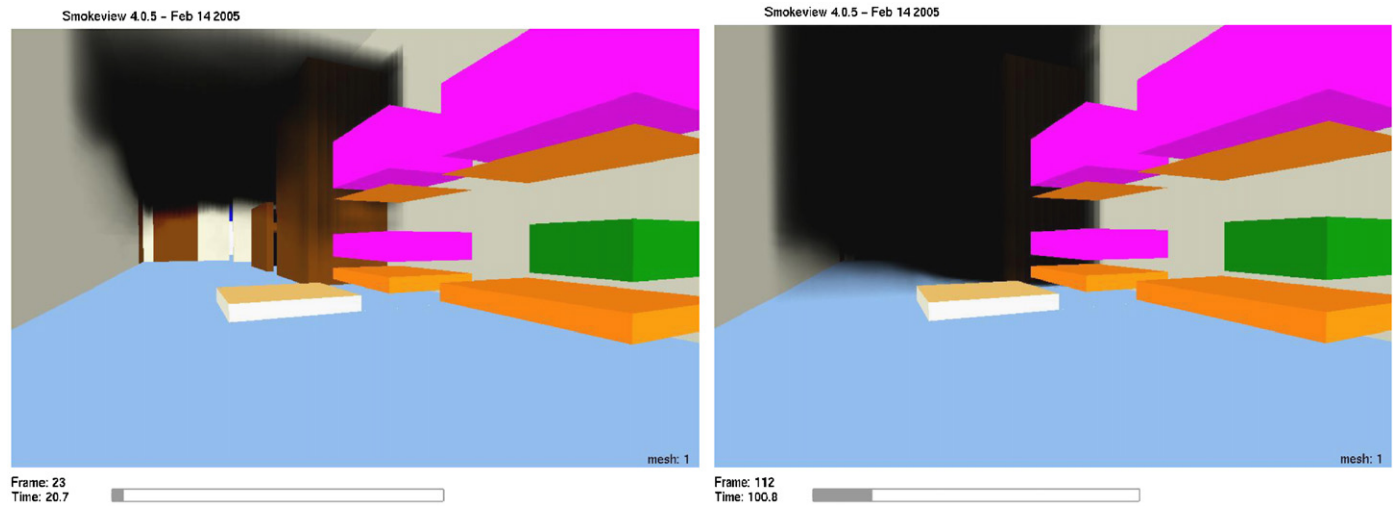
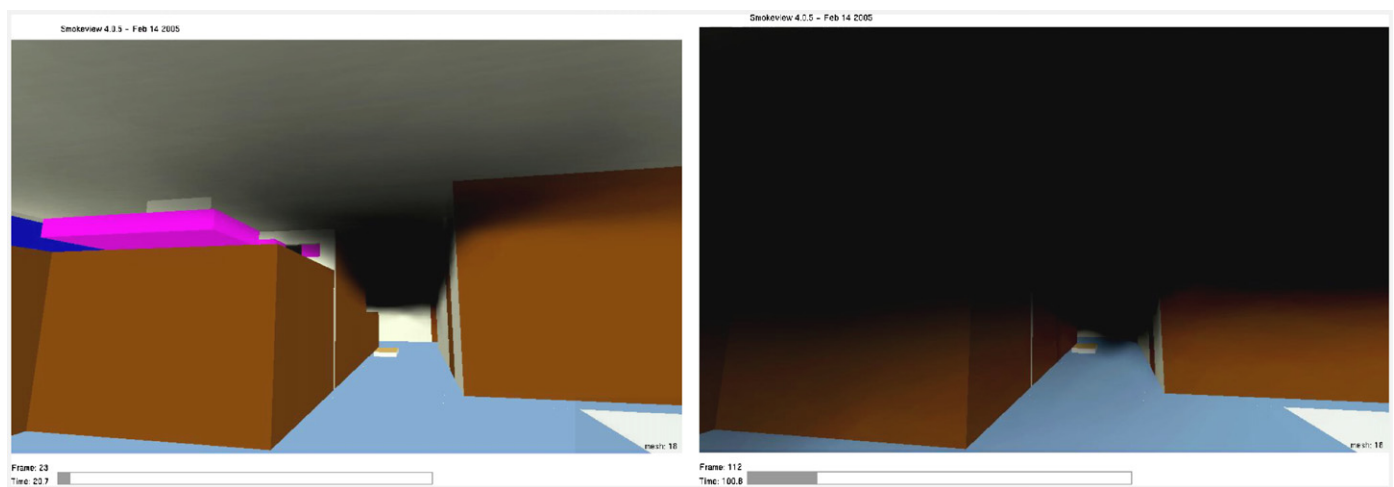Fig. 14. Smoke propagation profiles at fire source (20 s, 100 s).

Fig. 15. Smoke propagation profiles at service counter (20 s, 100 s).
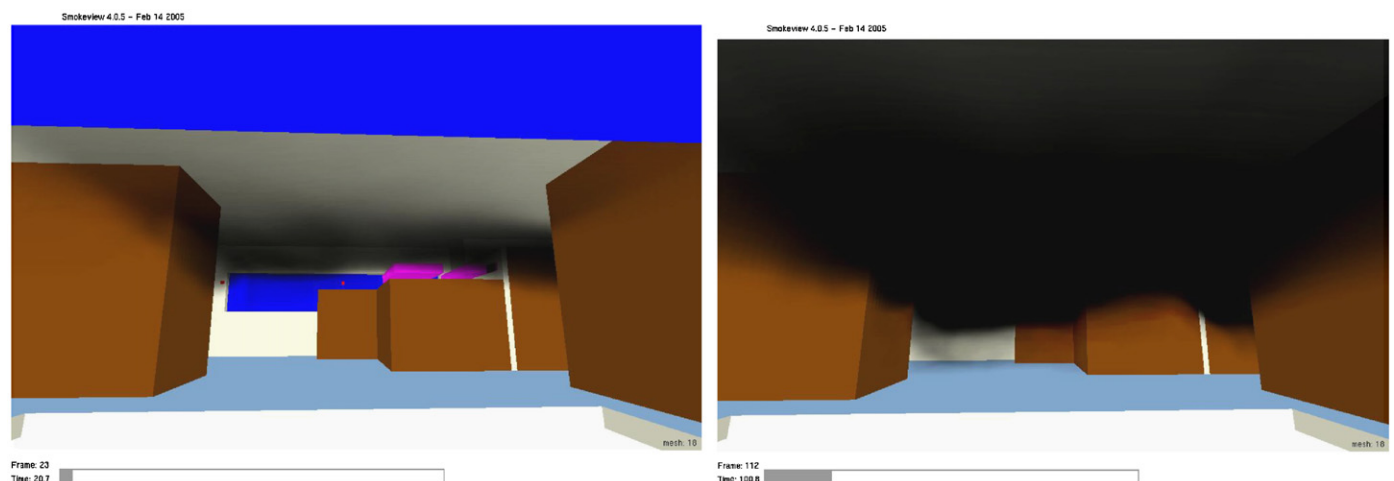

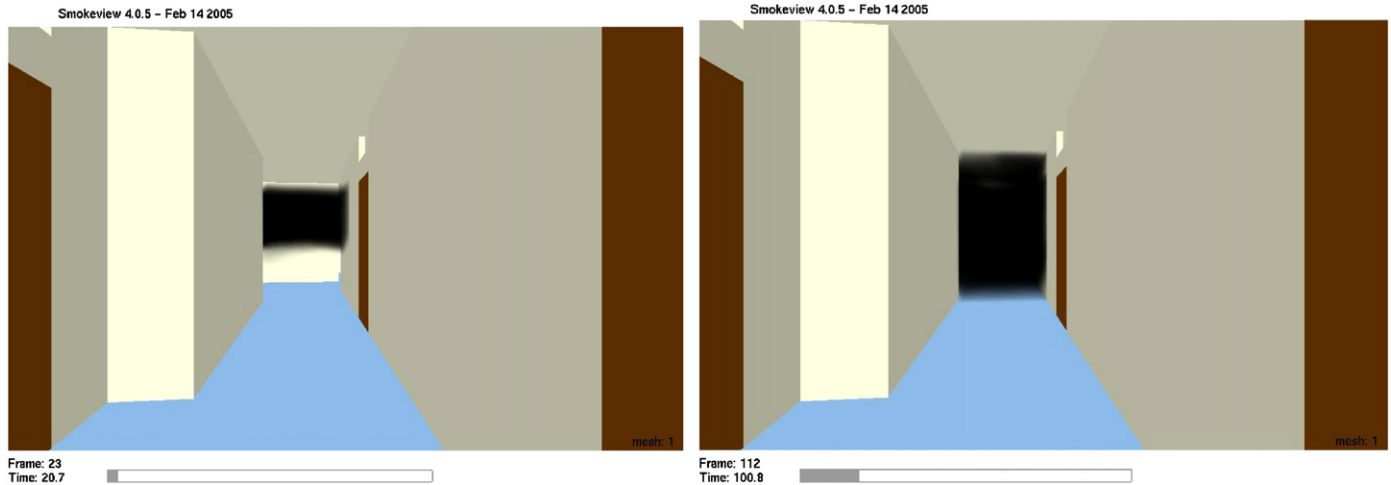Fig. 16. Smoke propagation profiles at lobby and storage room (20 s, 100 s).

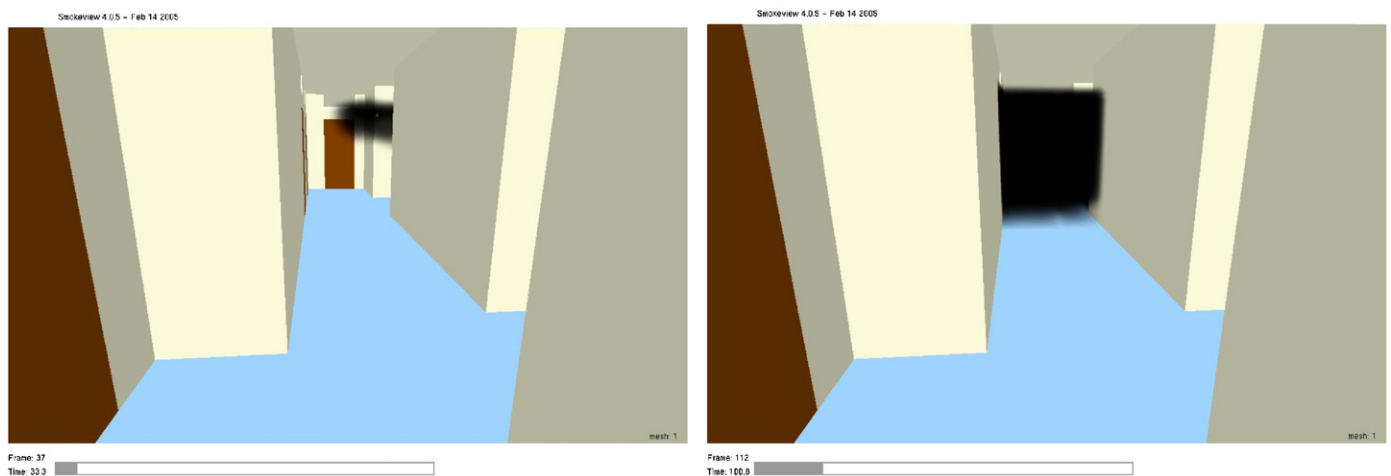Fig. 17. Smoke propagation profiles at R10 hallway (20 s, 100 s).

Fig. 18. Smoke propagation profiles at R18 hallway (33 s, 100 s).

fast as that caused by the accelerating agent the production of heat and smoke would not have been enough to block the escape route in such a short time.

(2) The total amount of gasoline spilt in two places of hotel was estimated to be about 15 L. In addition, consideration of the route to the fire scene and the convenience of carrying a container to the scene offered valuable information for the police investigating the possibility of arson.

(3) Fire simulation can provide information on fire growth and spread, smoke production and movement, which are all necessary to fire investigation, both in causes and the protection of life and property. A fire scene reconstruction supported by computer simulation can also offer important information to code and fire administrations.

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